Investigating the 2nd Knee: KASCADE-Grande

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Cosmic Rays around the knee: What is the origin of the knee(s)?

- Energy?
- Mass?
- Arrival directions?
- Interaction mechanism?

→ Large number of observables
→ Multi-detector system

Energy per nucleus $E$ (GeV) vs. $I(E) \times E^{2.5} (m^2 s^{-1} sr^{-1} GeV^{-1.5})$
KASCADE-Grande

= KArlsruhe Shower Core and Array DETector + Grande

Measurements of air showers in the energy range $E_0 = 100$ TeV - 1 EeV
KASCADE: multi-parameter measurements

- energy range 100 TeV – 80 PeV
- up to 2003: $4 \cdot 10^7$ EAS triggers
- large number of observables:
  - electrons
  - muons (@ 4 threshold energies)
  - hadrons
KASCADE: energy spectra of single mass groups

**Measurement:**
KASCADE array data
900 days; 0-18° zenith angle
0-91 m core distance
\( \lg N_e > 4.8; \lg N_{\mu}^{\text{tr}} > 3.6 \)
\( \Rightarrow \) 685868 events

**Searched:**
E and A of the Cosmic Ray Particles

**Given:**
\( N_e \) and \( N_{\mu} \) for each single event

\( \Rightarrow \) solve the inverse problem

\[ g(y) = \int K(y, x)p(x)dx \]

with \( y=(N_e, N_{\mu}^{\text{tr}}) \) and \( x=(E,A) \)
KASCADE result: influence on hadronic interaction model

same unfolding but based on two different interaction models: SIBYLL 2.1 and QGSJET01 (both with GHEISHA 2002)
KASCADE result: sensitivity to hadronic interaction models

Main results keep stable independent of method or model:
- knee caused by light primaries
- positions of knee vary with primary elemental group
- no (interaction) model can describe the data consistently

KASCADE collaboration, Astroparticle Physics (2005), accepted
KASCADE data analyses: shower observable correlations

Correlation of observables:
no hadronic interaction model describes data consistently!
⇒ tests and tuning of hadronic interaction models!
⇒ close co-operation with model builders
Recent highlights of KASCADE data analyses

Comparison with direct measurements

Reconstruction of the primary cosmic ray proton spectrum
Motivation for KASCADE-Grande

- second knee ??
- transition galactic-extragalactic CR ??

→ measure higher energies!
KASCADE-Grande: multi-parameter measurements

KASCADE + Grande
- energy range: 100 TeV – 1 EeV
- large area: 0.5 km²
- Grande: 37x10 m² scintillators
- Piccolo: trigger array
KASCADE-Grande: Status

- Common events (all detector components) measured since December 2003
- Trigger: 7 of 7 stations at one of 18 hexagons

100% efficient above $2 \times 10^{16}$ eV

600x600 m$^2$ $<42^\circ$

primary energy $\log(E_p/\text{GeV})$

trigger efficiency
KASCADE-Grande: Status

lateral distribution of a single event measured by KASCADE-Grande: \( E_0 \approx 2 \times 10^{17} \text{eV}, \Theta = 33^\circ \)
KASCADE-Grande: Reconstruction

1) core position and angle-of-incidence from Grande array data

2a) shower size (charged particles) from Grande array data

2b) muon number from KASCADE muon detectors

3) electron number from Grande by subtraction of muon content

4) two dimensional size spectrum for the analysis
KASCADE-Grande: Reconstruction

Monte-Carlo studies:
- Sufficient reconstruction accuracies for
  - core
  - direction
  - shower size, and
  - muon number

April, 30 2005 – Aspen, Colorado
Andreas Haungs – KASCADE-Grande Collaboration
‘Physics from the Knee to the Ankle’
KASCADE-Grande: lateral distributions

- Averaged electron lateral distribution
- Averaged muon lateral distribution per
  - reconstructed total muon number
  - electron shower size

θ<18°; core inside Grande array

preliminary
KASCADE-Grande: first analyses

Unfolding of 2-dimensional shower size spectrum → composition

Unfolding of 2-dimensional shower size spectrum

- Electron size
- Muon size

Preliminary plots showing the number of showers as a function of shower size and electron/muon size.
KASCADE-Grande: size spectra

1-dimensional shower size spectra after ~1 year of Grande measurements

**electron size**

![Graph showing electron size spectra with different angular ranges: 0°-18°, 18°-25°, 25°-30°.](image)

**muon size**

![Graph showing muon size spectra with different angular ranges: KASCADE-Grande 0°-18°, KASCADE-Grande 18°-25°, KASCADE 0°-18°, KASCADE 18°-25°.](image)

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'Physics from the Knee to the Ankle'
KASCADE-Grande: muon density measurements

redundant shower information enables Monte-Carlo tests!

Sensitive parameters for consistency checks of the simulated air-shower development up to $10^{17.8}$ eV primary energy.

$$R_\rho = \frac{\rho^{\mu}_p}{\rho^{\mu}_T}$$

at MWPC $\rho^{\mu}_p$: $E^{21h}_\mu = 2.1$ G

at TP $\rho^{TP}_\mu$: $E^{21h}_\mu = 490$ MeV

$R < 325$ m

$R_{CD} = 30$ m - 550 m
KASCADE-Grande:
Flash ADC system

- Flash-ADC system for the Grande array

with optical links and a ring buffer system

- self triggering
- full signal information of the detectors
- high time resolution
- intrinsic electron muon separation

High precision data from Grande array
KASCADE-Grande: Radio shower detection

- Deflection of electron-positron pairs in the Earth's magnetic field → coherent emission at low frequencies
- With radio detection → see shower development → observe 24 hrs/day
- 30 dipole antennas at KASCADE-Grande
- Calibration of radio emission
- Theory of radio emission and implementation in CORSIKA
- Improvement/optimisation hardware (for application in Auger)

LOPES collaboration:
- KASCADE-Grande
- U Nijmegen, NL
- MPIfR Bonn, D
- Astron, NL
- IPE, FZK, D
LOPES: Radio shower detection

- 10 antennas at KASCADE frequency band 40-80 MHz
- trigger: >10/16 cluster of KASCADE (E_0 > 10^{16} eV)

2005:
- sample of events for detailed analysis
- upgrade to 30 antennas

Event analysis

Publication is in print
KASCADE-Grande:
Summary

• Single element spectra reconstruction is possible by EAS measurements (KASCADE)
  ➔ Knee is caused by light primary elements, cosmic rays are isotropic around the knee
• Data distributions are not consistent with Monte Carlo predictions
  ➔ Interaction models have to be further improved

• KASCADE-Grande will cover whole „knee“ range to find the „iron“-knee!
• Radio detection as new technique for UHECR measurements

AGASA-Akeno
KASCADE (all)
KASCADE (Fe)
Extragalactic p
Fe-model

Aloisio, Berezinsky astro-ph/0412578

Grande $E_0$-range